Electro-thermal-mechanical Simulation and Reliability for Plug-in Vehicle Converters and Inverters

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Project ID # APE 026

This presentation does not contain any proprietary, confidential, or otherwise restricted information

Overview

Work Timeline

- June 2011
- June 2014
- 40% Complete

Budget

- Total project funding
  - $700K
- Funding received in FY11
  - $ 200K
- Funding received in FY12
  - $ 300K
- Funding expected in FY13
  - $ 200K

Barriers

Need electro-thermal-mechanical modeling, characterization, and simulation of advanced technologies to:

- Improve electrical efficiency
- Improve package thermal performance and increase reliability
- Reduce converter cost

Partners

- NIST- Electro-thermal modeling
- UMD/CALCE – Reliability modeling
- VTech – Soft switching module
- Delphi – High current density module
- Powerex – Module technology
- NREL – Cooling technology

Goal: Electro-Thermal-Mechanical Simulation

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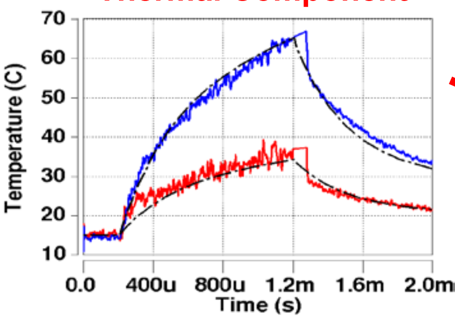
Energy Efficiency & Renewable Energy

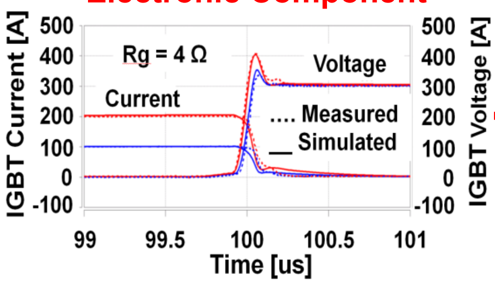
USDRIVE
DRIVING RESEARCH AND INNOVATION FOR VEHICLE EFFICIENCY AND ENERGY SUSTAINABILITY

Models, Parameter Determination

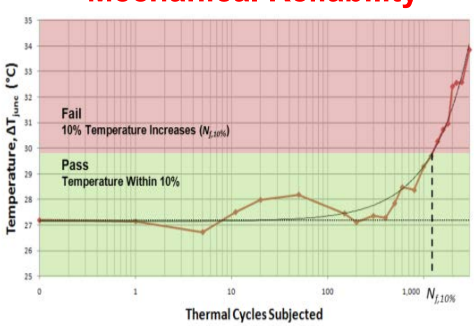
Thermal Component



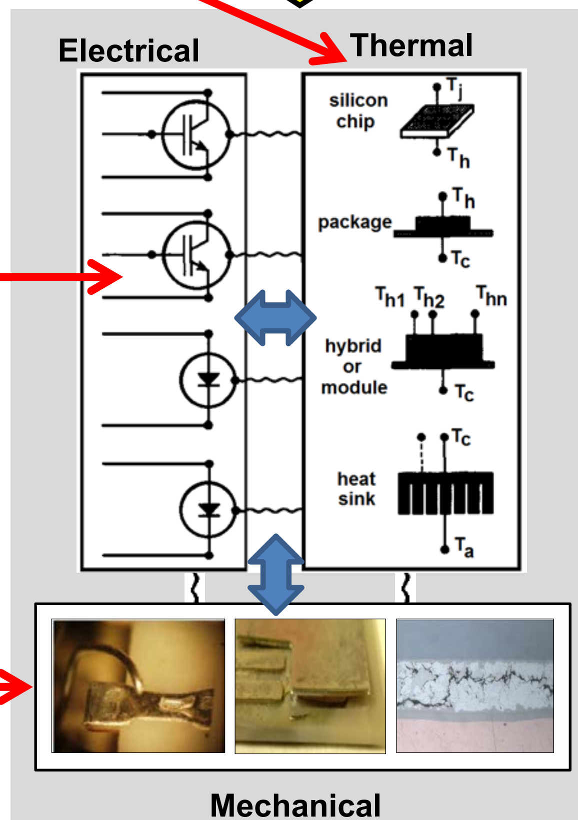
Electronic Component



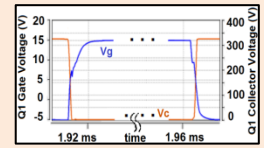
Mechanical Reliability



Driving Cycles, Environmental Conditions

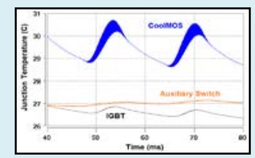


Simulation Applications



Electrical

- Inverter performance evaluation
- Advanced topology design
- Advanced device integration



Electro-Thermal

- Electro-thermal interactions,
- SOA and failure mechanisms,
- Cooling system impacts.

Reliability

- Reliable integration of advanced technologies
- System reliability evaluation.

- In-Vehicle applications:
  - Maintaining component health,
  - Predicting service needs,
  - Operation with partially degraded capacity near component end-of-life.

NIST calce NREL VT POWEREX DELPHI

Relevance

Objective:

Provide theoretical foundation, measurement methods, data, and simulation models necessary to optimize power module electrical, thermal, and reliability performance for Plug-in Vehicle inverters and converters.

FY 2013 Goals:

1) Analyze Viper SOA using dynamic electro-thermal simulation with models including high voltage, high current parameter extraction
2) Develop Cross-Coupling TSP Measurement capability and use to validate thermal coupling model within VTech Module Thermal Model
3) Develop Thermal Component Models for Air and Liquid Cooled Heatsinks and include in electro-thermal simulation of Viper and VTech modules
4) Perform thermal cycle measurements to extract parameters for Physics-of-Failure Models and use in Electro-Thermal-Mechanical Simulation
5) Develop electro-thermal models for advanced semiconductor devices e.g., SiC MOSFETs and SiC JFETs and GaN diodes.

Milestones/Decision Points

Month/Yr	Milestone
Aug. 12 (complete)	1) Used electro-thermal-mechanical simulations to validate measurement during fault conditions and evaluate thermal stresses in Viper module.
July 13 (Go,no-Go)	2) Incorporate Failure Models into Electro-Thermal Simulation using results of thermal cycling degradation and monitoring measurements on two DBC stacks.
Sept. 12 (complete)	3) Developed thermal-network-component models for representative cooling systems.
Oct. 12 (on hold)	4a) Used simulations to evaluate thermal stresses at module interfaces for VTech module, 4b) and use physics of failure models to calculate damage and evaluate impact on VTech module life.
Jan. 13 (on hold)	4c) Calculate increase in thermal resistance at interfaces in VTech module due to thermal cycling damage and use changing resistance in the thermal network during simulations.
Mar. 13 (complete)	5) Included liquid- and air-cooling thermal network component models in electro-thermal simulations of vehicle inverters.
June. 13 (ongoing)	6) Developed electro-thermal models for advanced semiconductor devices including SiC MOSFETs, SiC JFETs and GaN diodes.
Aug. 13 (ongoing)	7) Include advanced Wide-Bandgap semiconductor device models in simulations to optimize high current density, low thermal resistance, and soft-switching modules.

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FY13 Tasks to Achieve Goals

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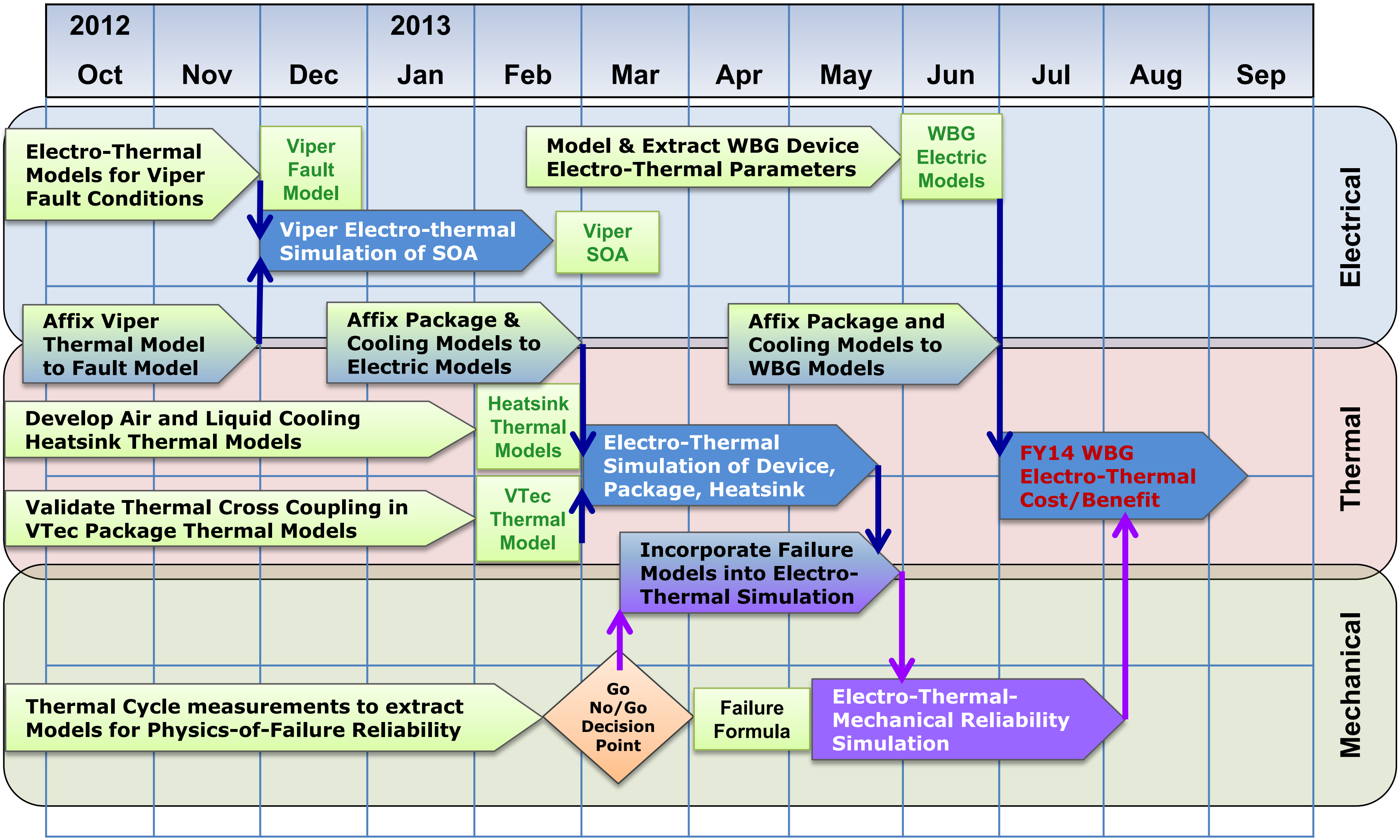
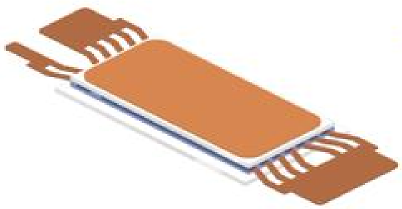


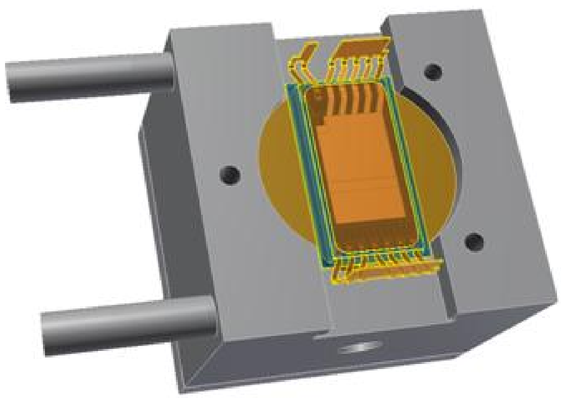
NIST calce NREL VT POWEREX DELPHI

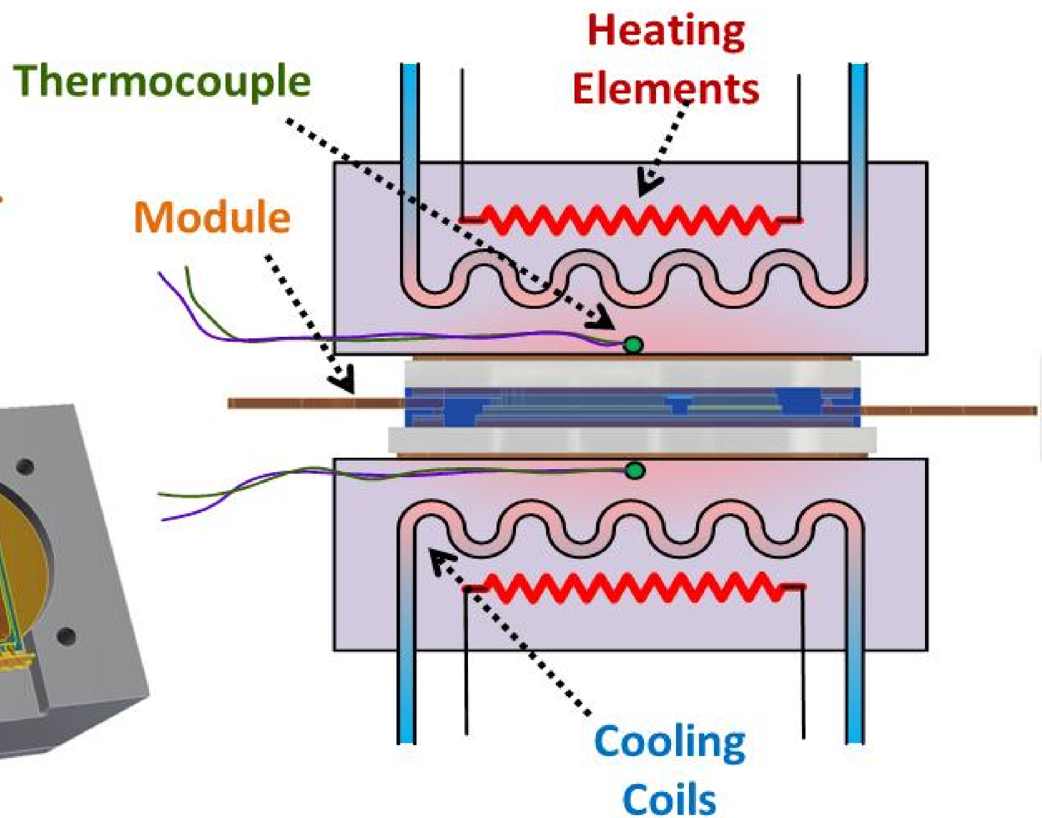
Approach: Measurement, Modeling, and Simulation

- **Develop dynamic electro-thermal Saber models, parameter extractions, and validation of models for:**
  - Silicon IGBTs and PiN Diodes
  - Silicon MOSFETs and CoolMOSFETs
  - SiC Junction Barrier Schottky (JBS) Diodes
  - SiC MOSFETs
- **Develop thermal network component models and validate models using transient thermal imaging (TTI) and high speed temperature sensitive parameter (TSP) measurement:**
  - Power Semiconductor Chip
  - Package: Delphi VIPER and VTech Soft Switching modules
  - Air and liquid cooling heatsinks
- **Develop thermal-mechanical degradation models and extract model parameters using accelerated stress and monitoring:**
  - Stress types include thermal cycling, thermal shock, power cycling
  - Degradation monitoring includes TTI, TSP, X-Ray, C-SAM, etc.

Application: Delphi Viper Module Double-Sided Cooling Model

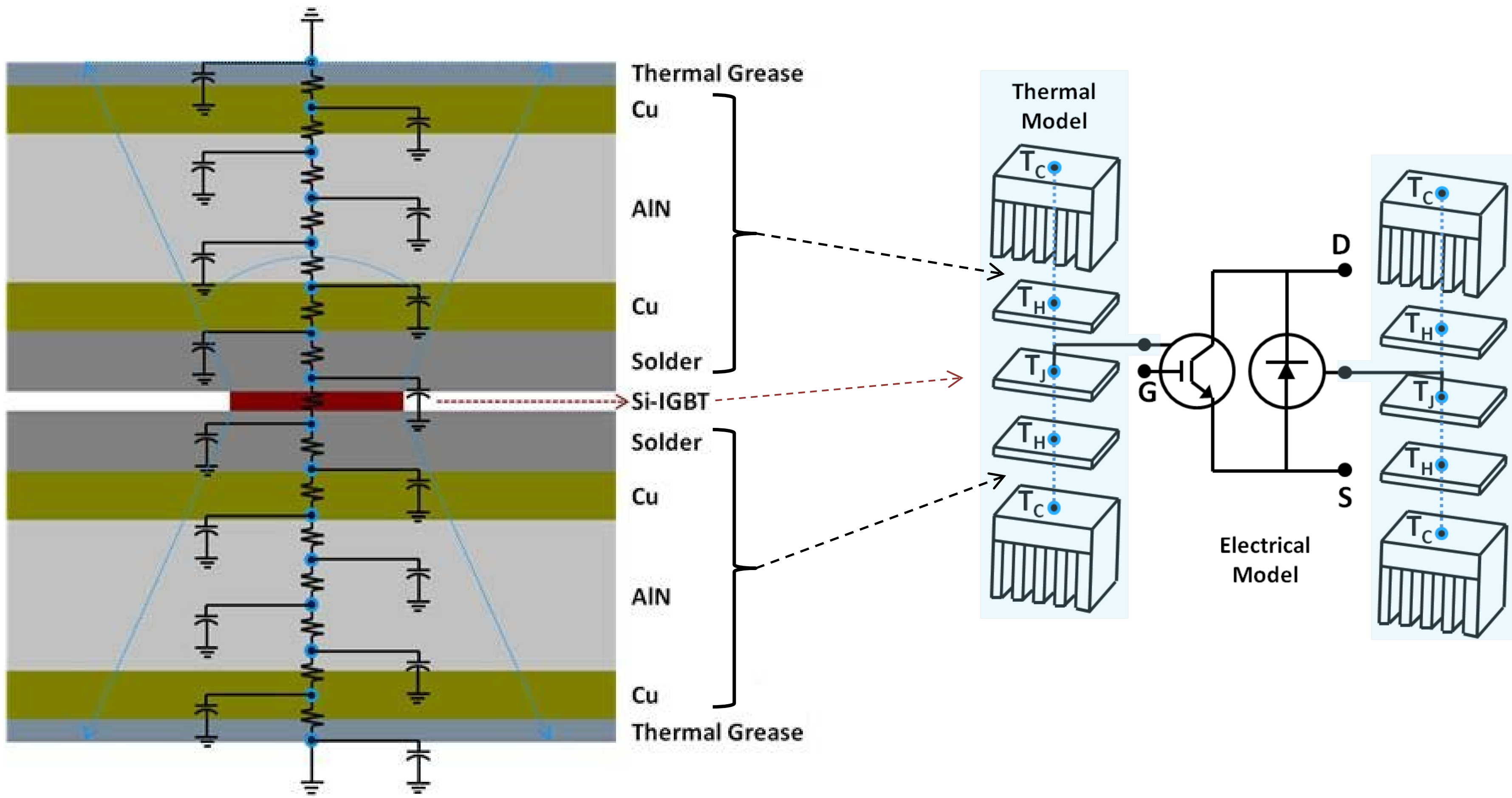




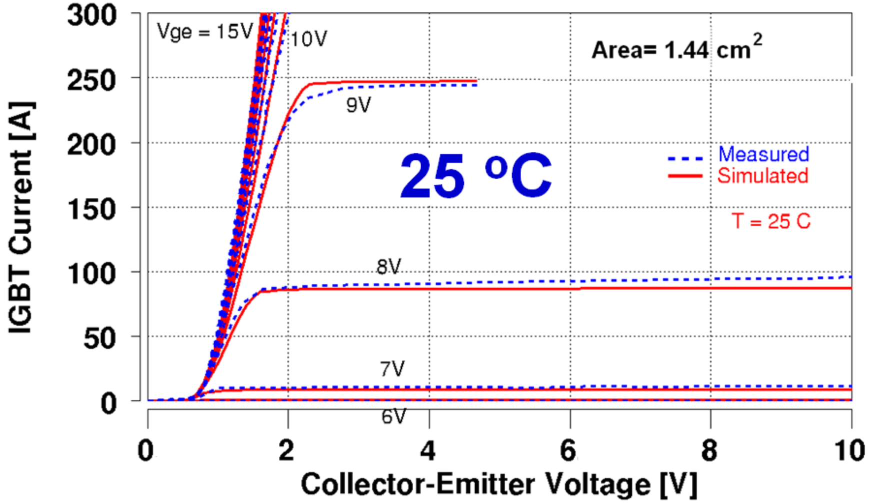


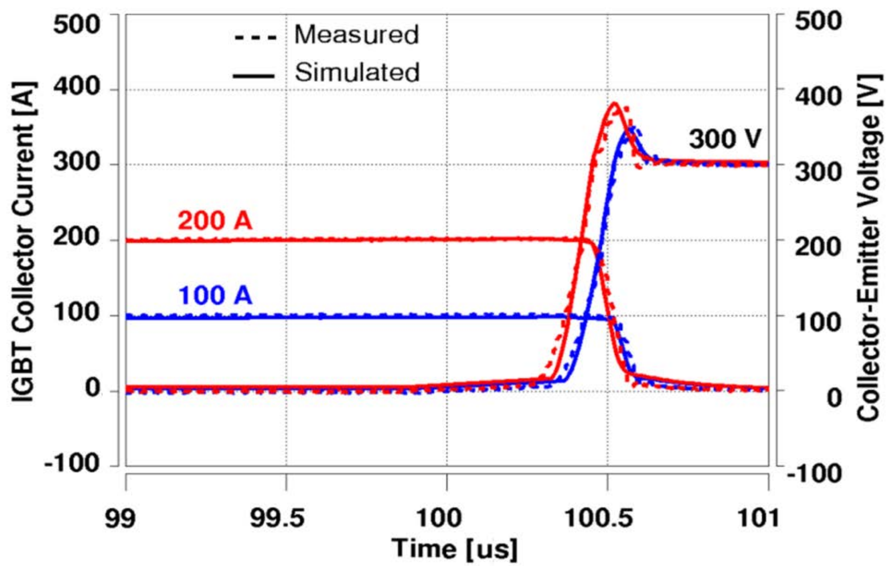
A doubled-sided temperature-controlled heatsink that was developed for the Viper module. This heatsink uses a spring-loaded piston to apply a controlled four kg compressional pressure to the device.

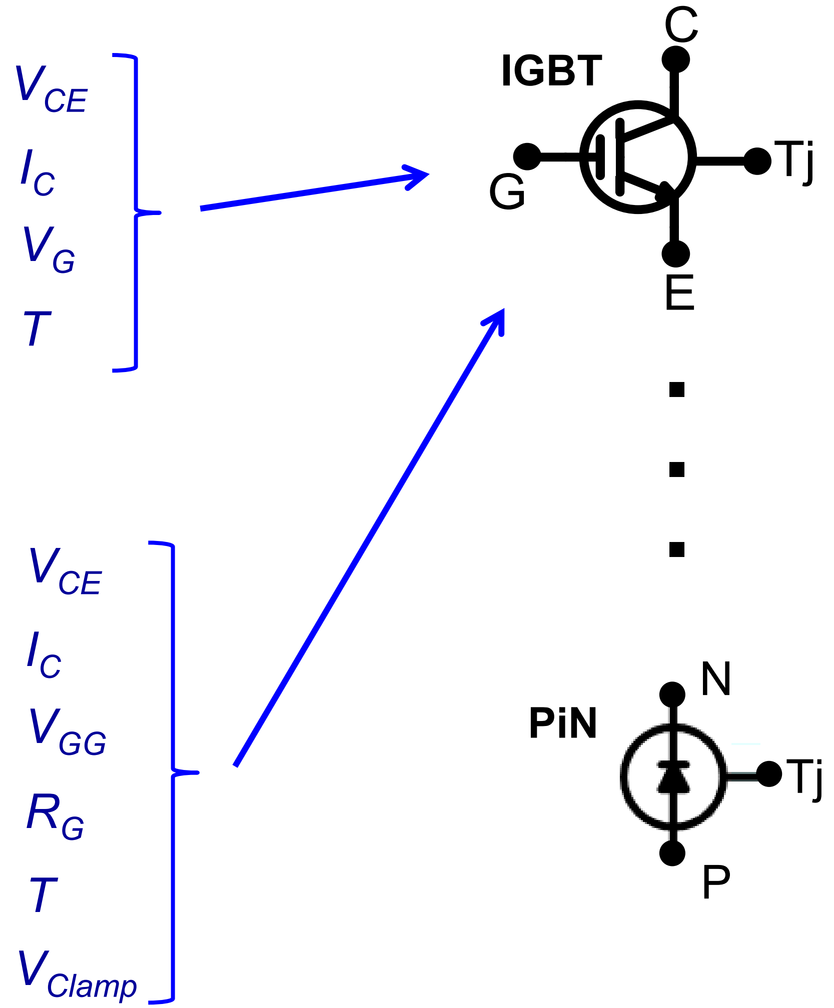
Method: Electro-Thermal Model for Double-Sided Cooling Viper Module



Validation: Delphi-Viper Electro-thermal Semiconductor Models



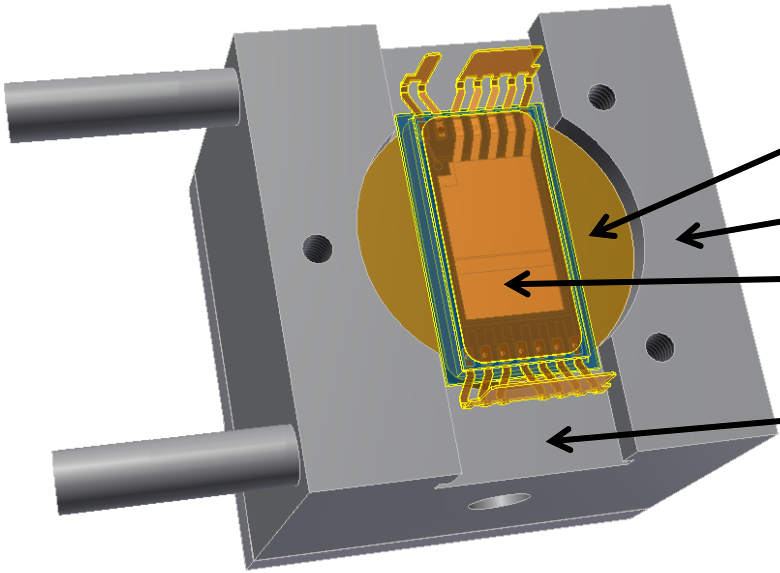




Additional validation results given at FY12 PEEM Kickoff meeting.

Validation: Thermal Test Fixture Model

Viper module thermal test fixture



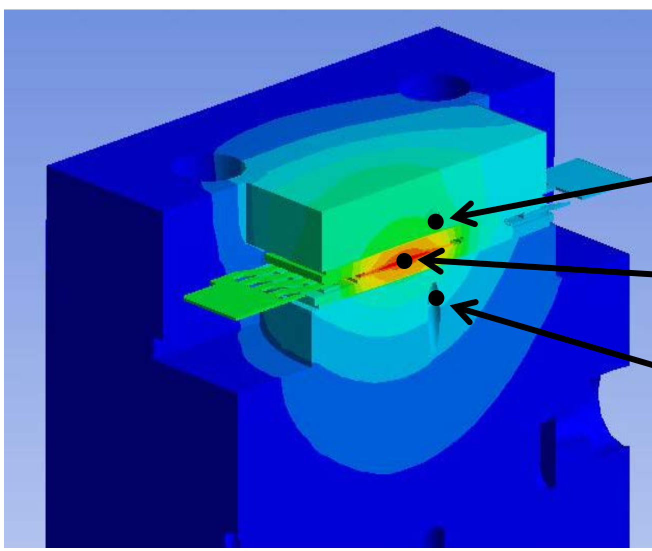
Piston

Top Cooling Plate (not shown)

Viper Module

Water Cooling Fixture

Viper module 262 W steady state ANSYS simulation for double-cooled test fixture



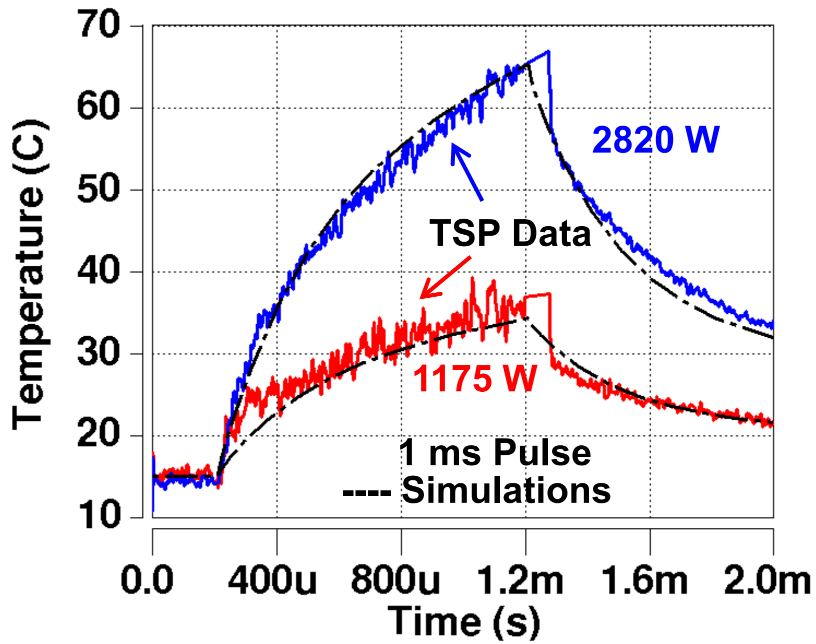
Top Plate Temperature (0.05" from edge)
37 °C (ANSYS model)
40.4 °C (Measurement)

Device Temperature
69 °C (ANSYS model)

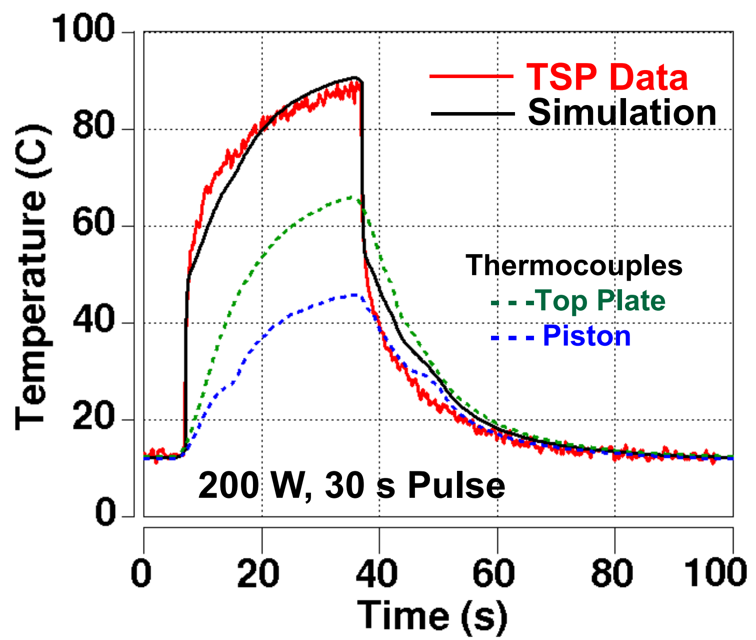
Piston Temperatures (0.05" from edge)
28 °C (ANSYS model)
31.7 °C (Measurement)

Validation: Thermal Network Component Model for Viper Module Package

- Test fixture used to validate thermal model of Viper die, package, and interface to copper plates using TSP measurements.
- Test fixture modeled and compared with ANSYS and TSP.

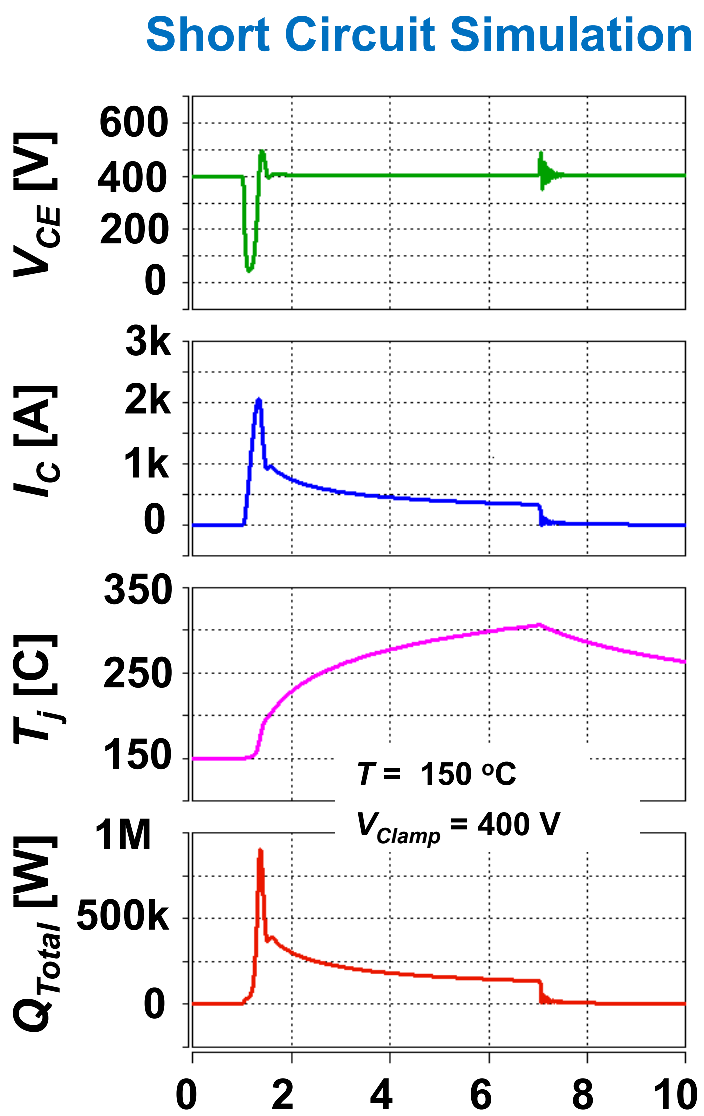


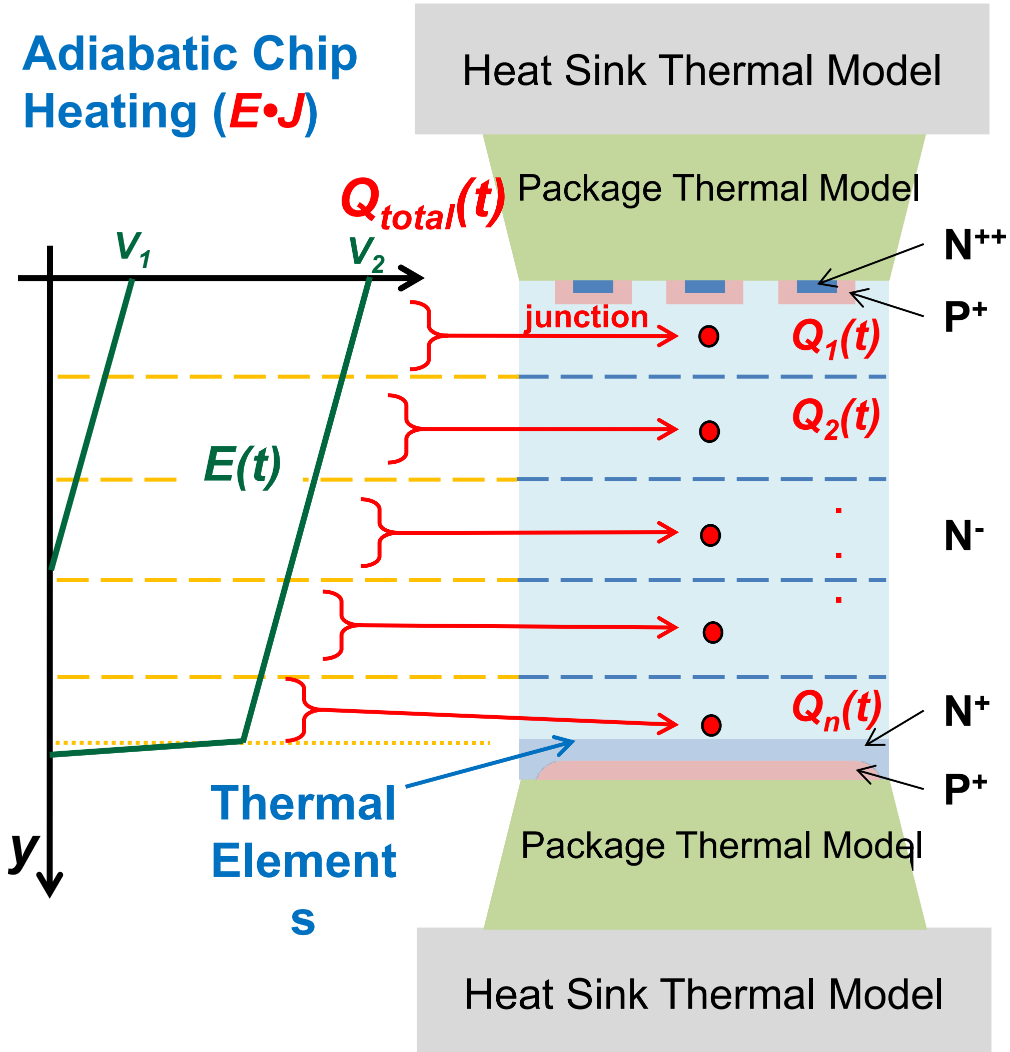
Comparison of simulated and measured Junction Temperature (TSP) for short duration, high power pulses.



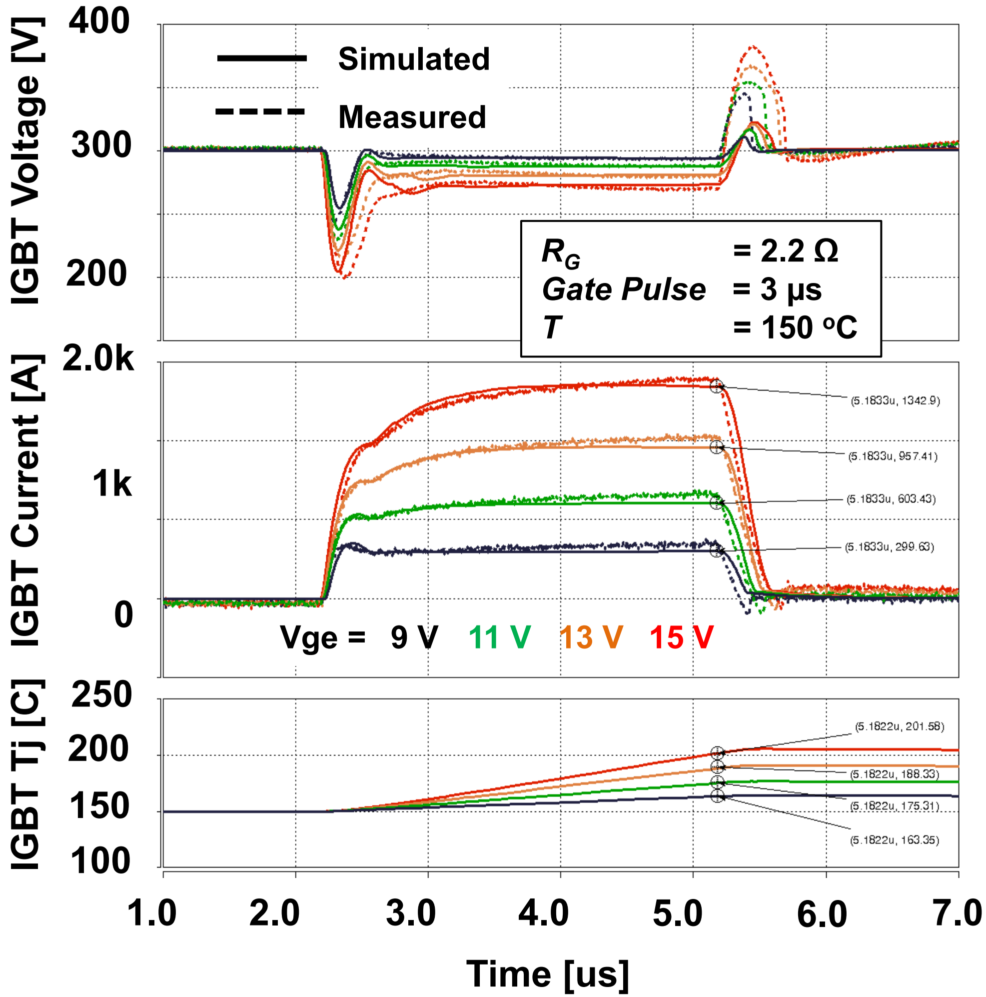
Comparison of simulated and measured Junction Temperature (TSP), and Plate and Piston Temperatures (thermocouples) for a low power, long duration pulse.

Method: Electro-Thermal Simulation Adiabatic Heating for Short Circuit Conditions





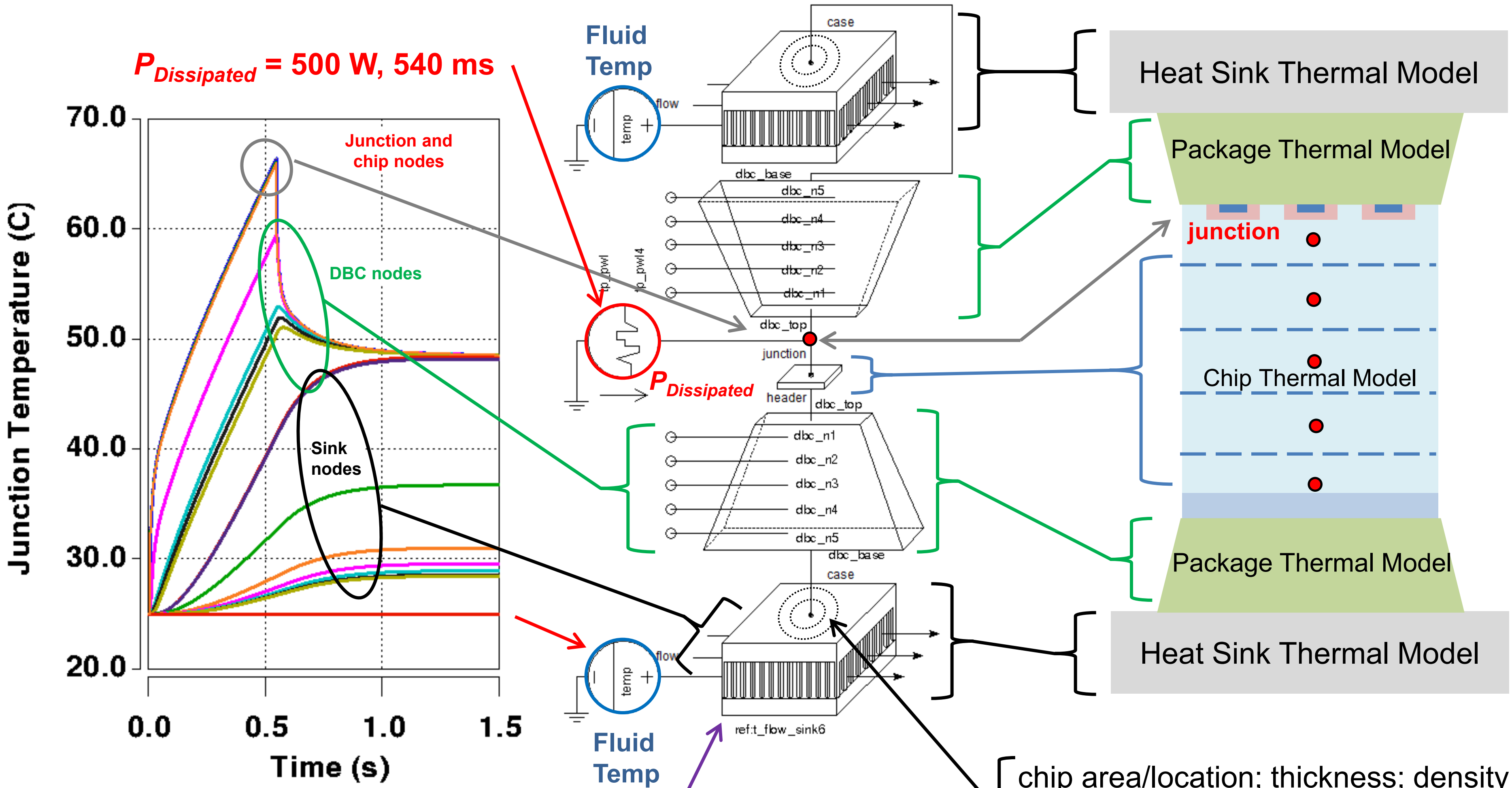
Demonstration: Viper Module Simulation for Short Circuit Conditions



Required Tasks:

- Extend and Validate Viper IGBT model for high voltage, high current conditions
  - short pulse to reduce heating
  - characterize gate, collector and common emitter R & L
  - vary Vg, Rg, Vc, and T to characterize IGBT model
- Thermal model validation using longer short circuit pulse
- Then, use model simulations to analyze SOA performance

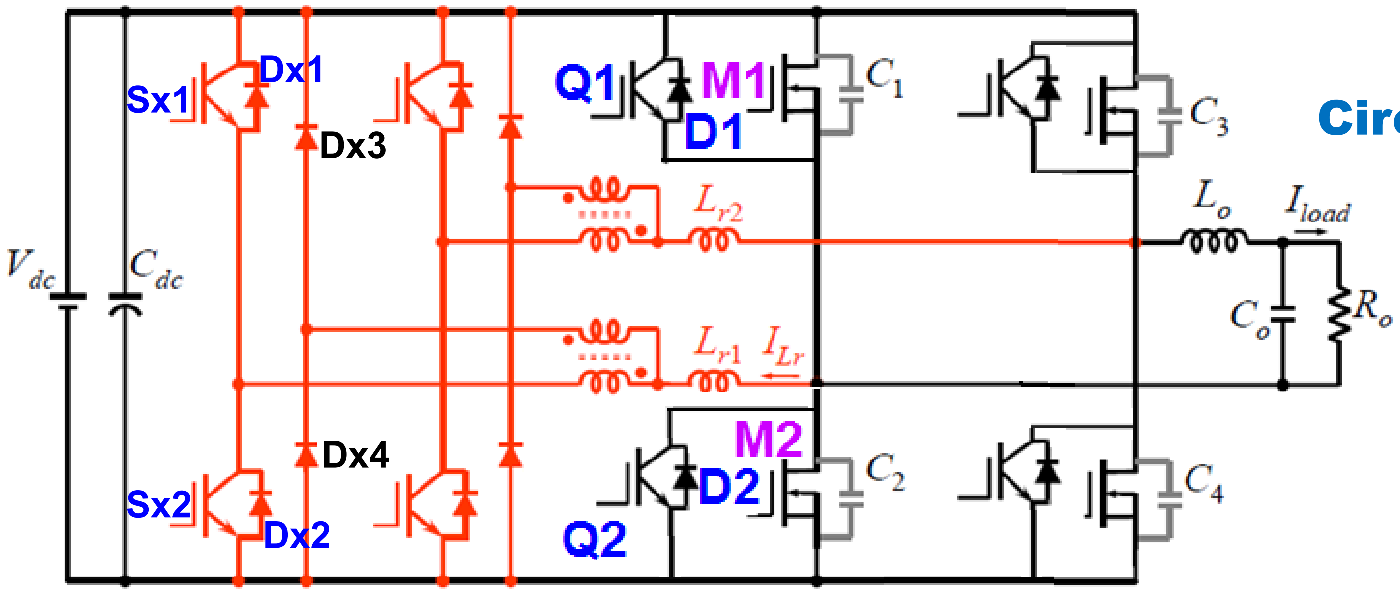
Demonstration: Liquid-Cooled Heatsink Viper Module Thermal Simulation



chip area/location; thickness; density heat capacity; thermal conductivity

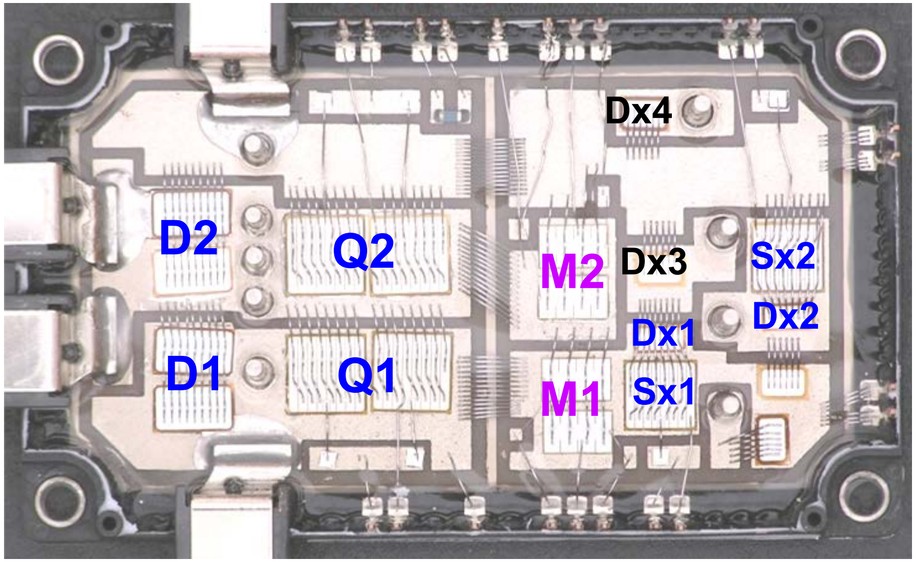
h_{eff} = 2 W/(K·cm²) – fluid properties, flow rate; number of fins; fin area; fin structure

Application: VTech Soft Switching Module

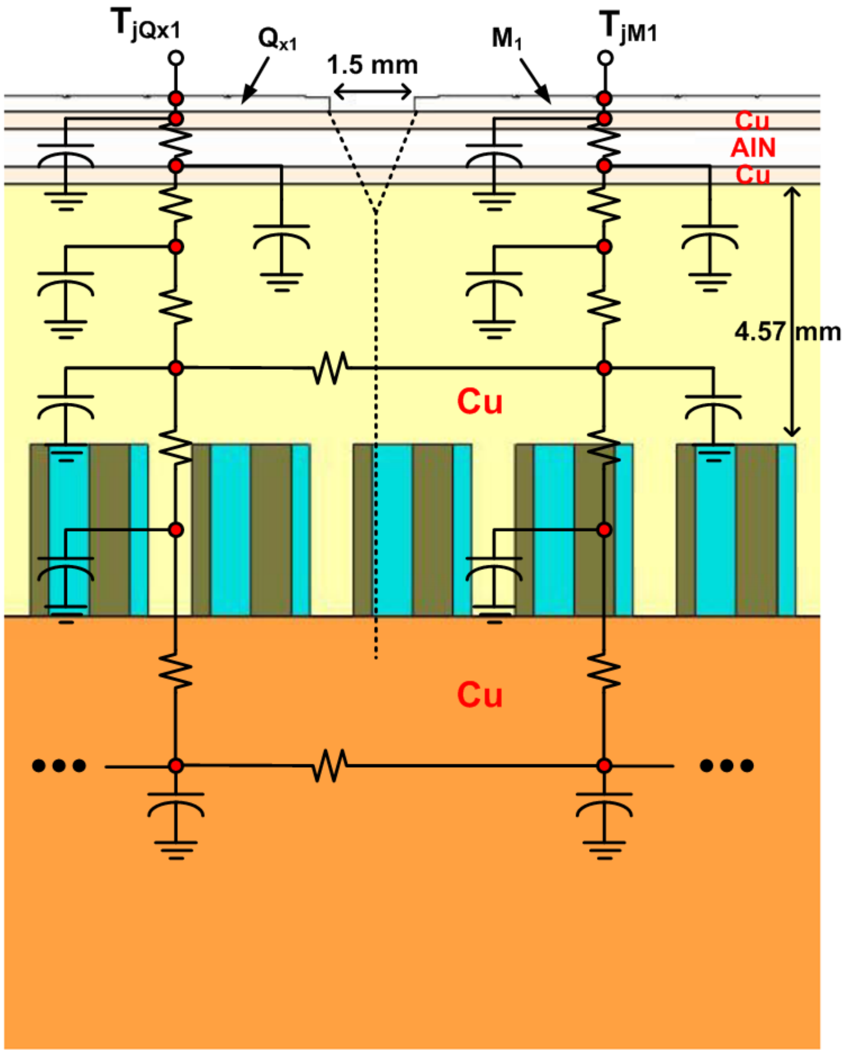


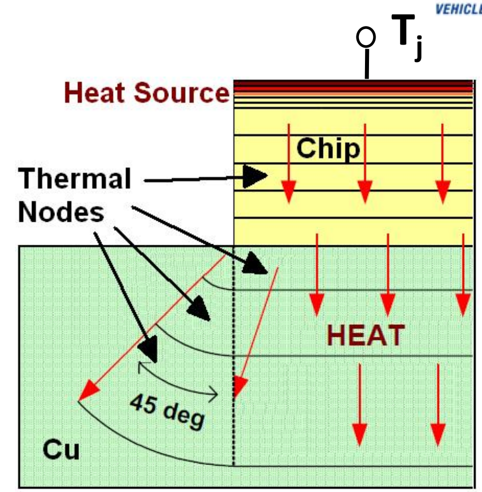
Circuit Diagram

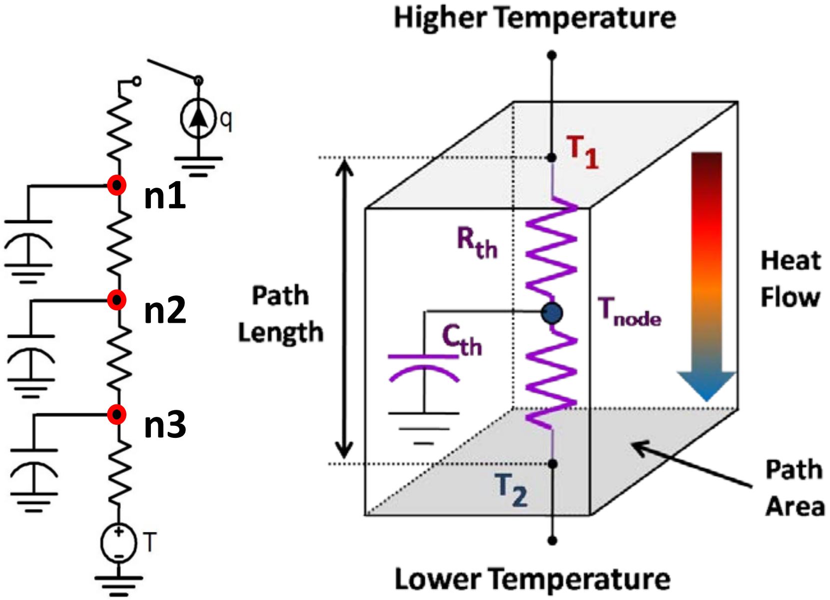
Module Components



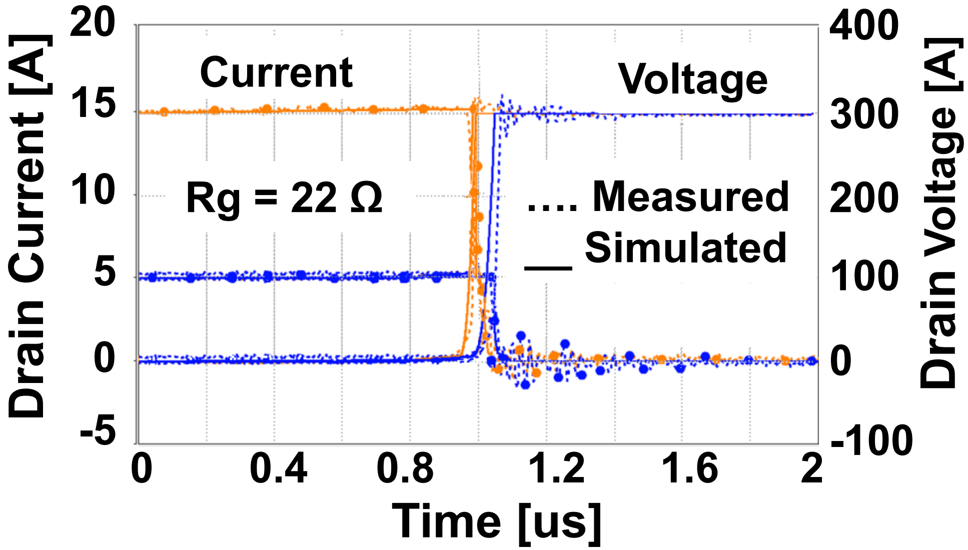
Method: Thermal Network Component Models

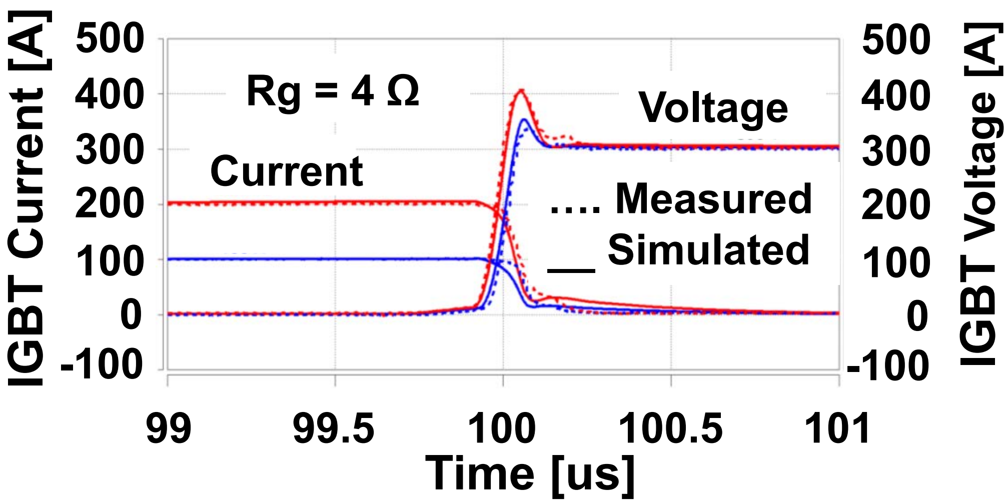


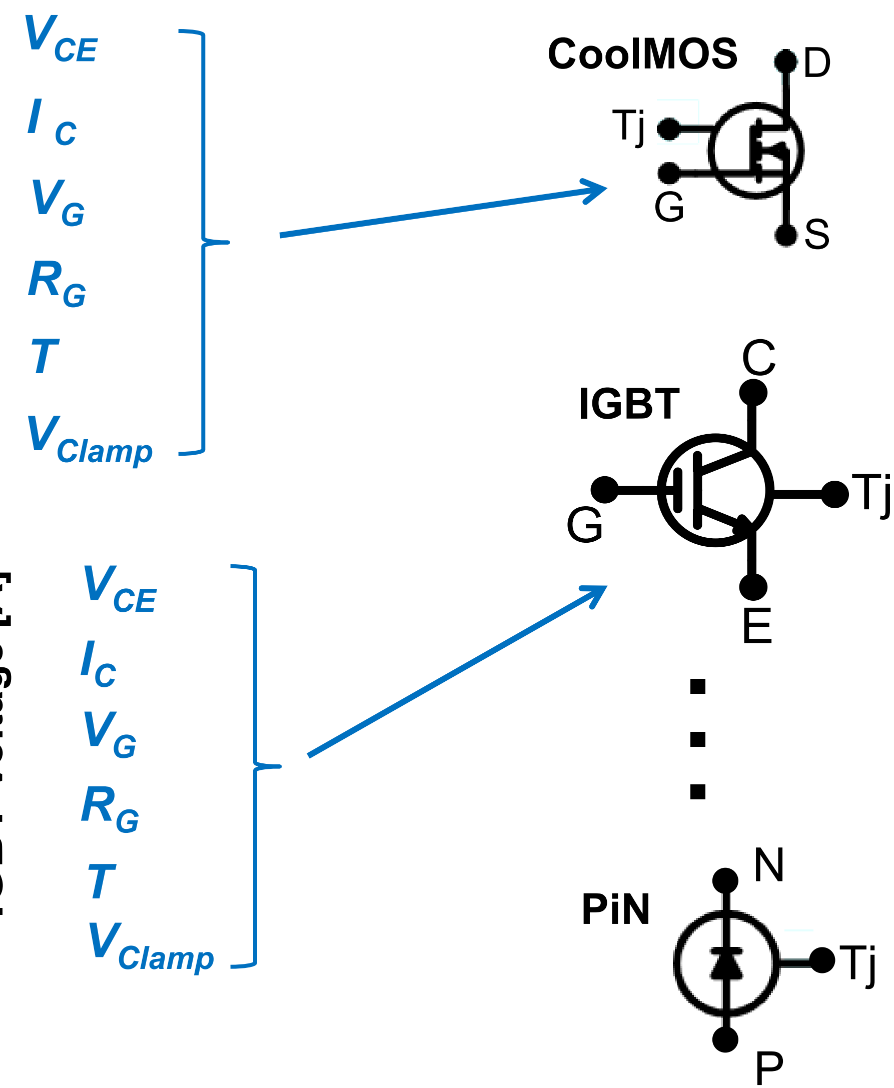




Validation: VTech Module Electro-thermal Semiconductor Models



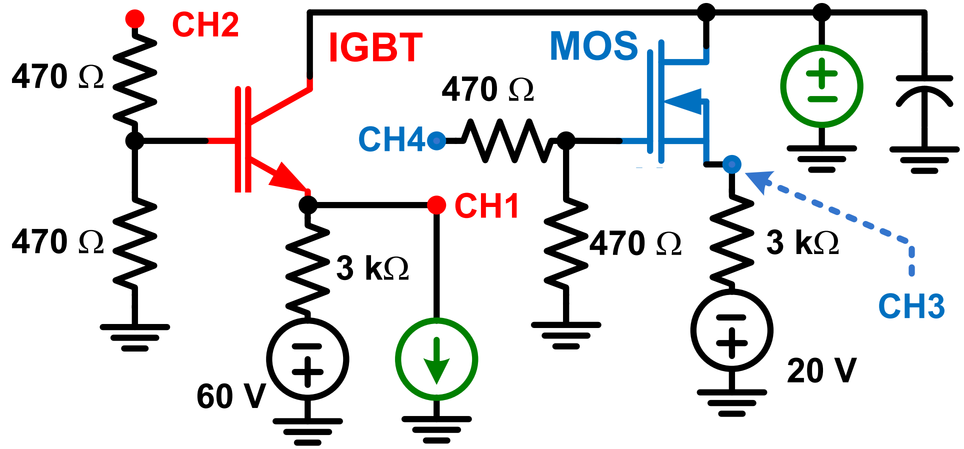




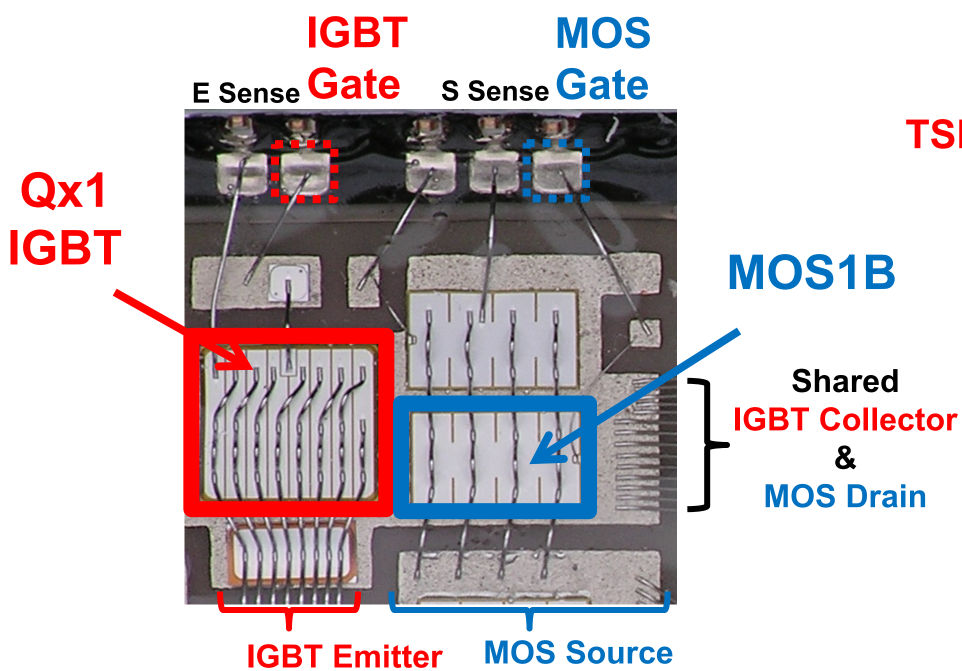
Additional validation results given at FY12 PEEM Kickoff meeting.

Method: Cross-Coupling TSP Measurement For VTech Module Paralleled IGBT/MOSFET

For the method to work, the **IGBT** has to dissipate a given **power** while the **MOSFET** remains off, and their gates must be measured independently.

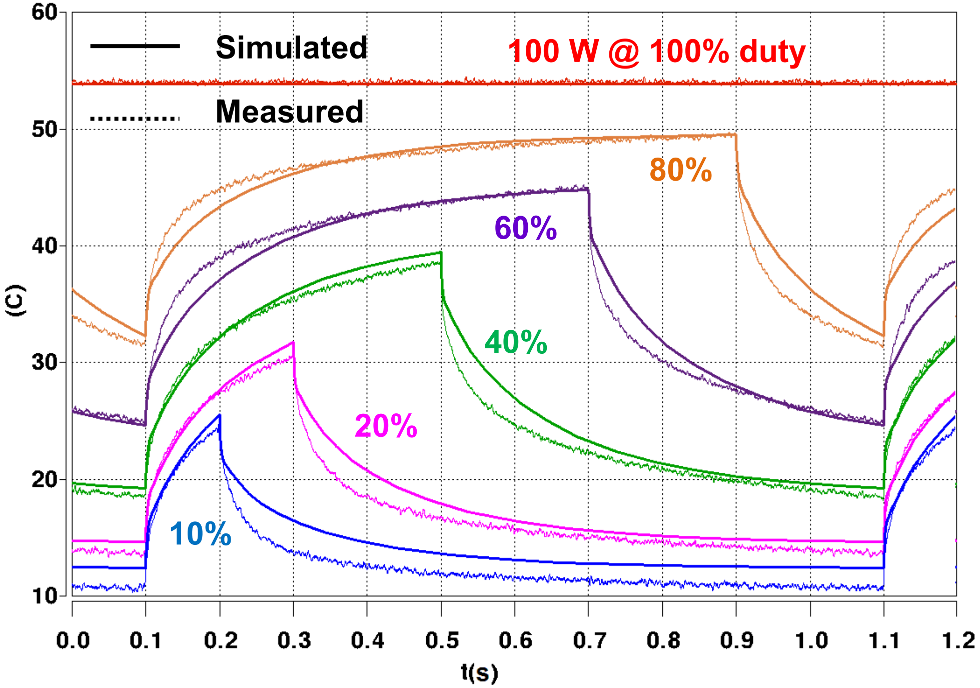


$TSP_{IGBT} = V_{CH1} - V_{CH2}$ $\quad$ $TSP_{MOS} = V_{CH3} - V_{CH4}$



The devices were chosen for having physical proximity, different power dissipation ratings, and being thermally coupled through the same conductive layer on top of the DBC

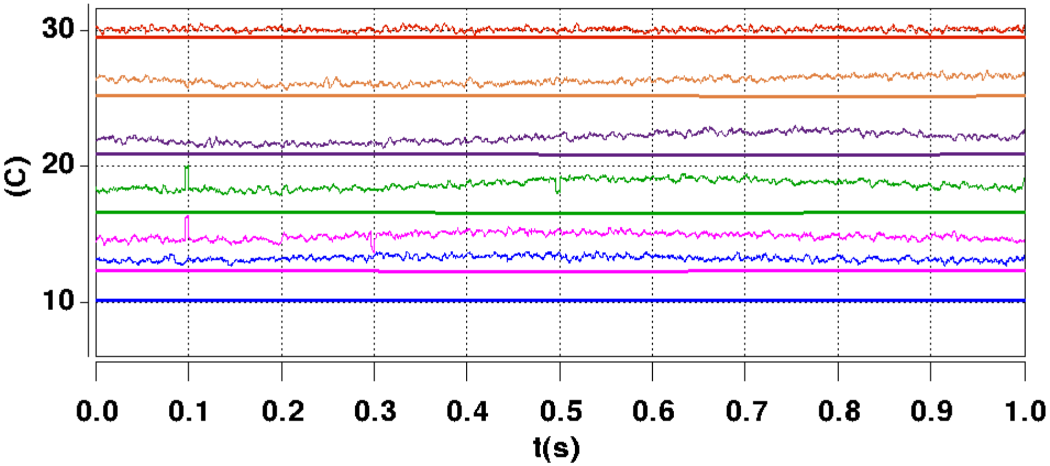
Validation: Cross-Coupling TSP Measurement VTech Module Thermal Coupling Model



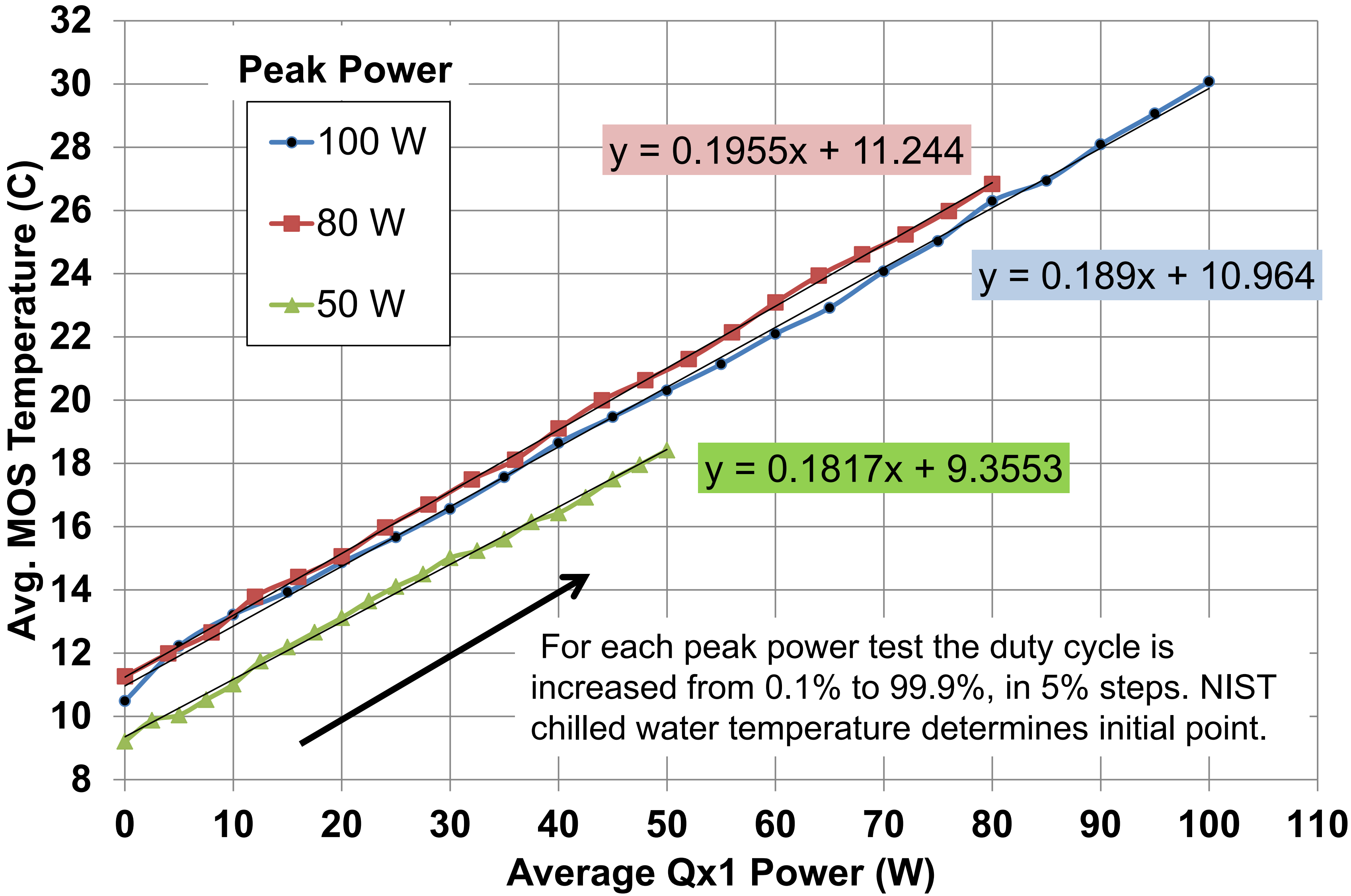
The IGBT was powered with a train of pulses at different duty cycles to generate enough average heat to be sensed in the MOS vicinity.

This IGBT measurements were used to validate the thermal transient behavior for the thermal stack model, and the MOS measurements were used to validate the thermal coupling model between adjacent power devices.

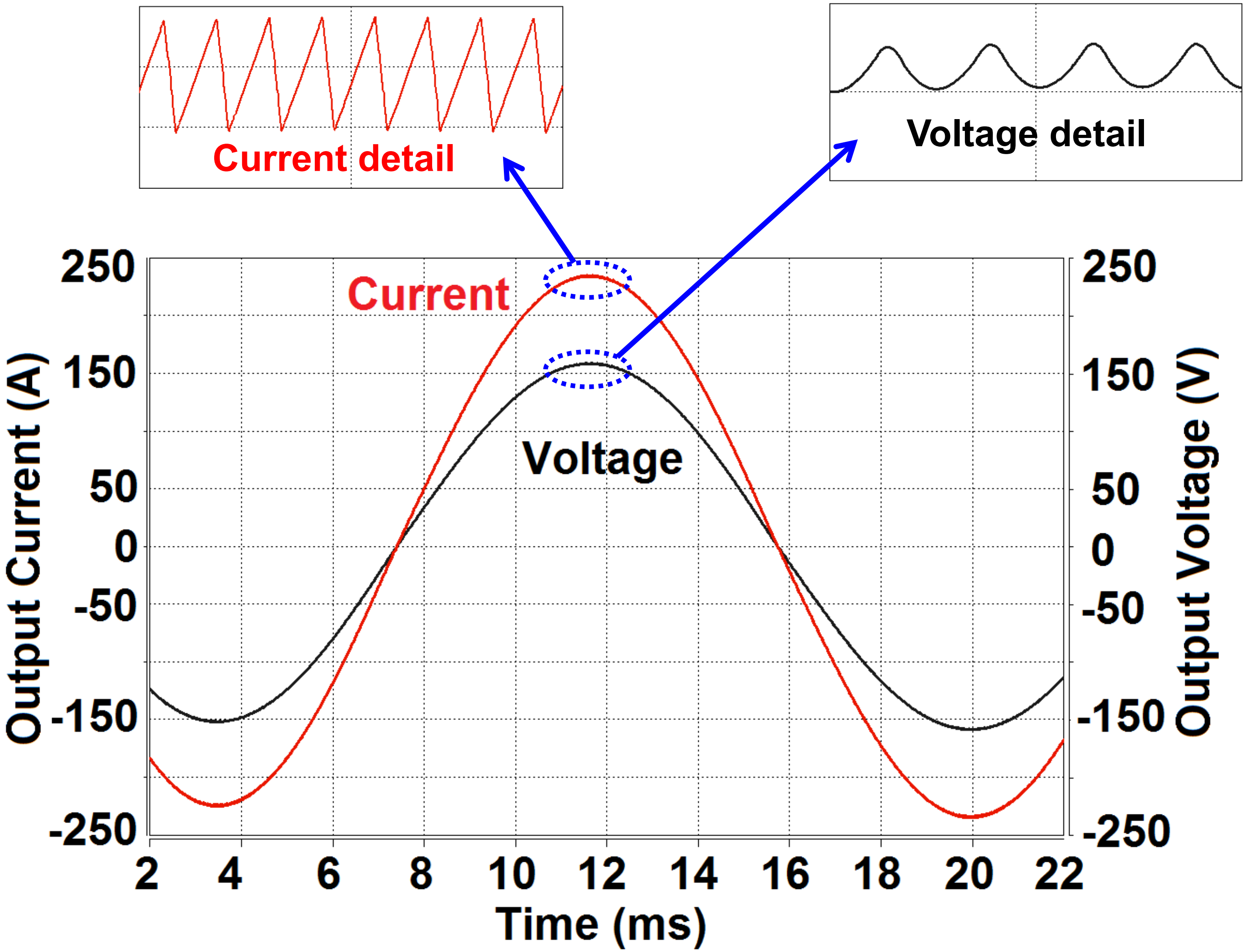
Preliminary electro-thermal coupling model results for the MOS measurements show a close correspondence in their behavior.



Analysis: Cross-Coupling TSP Measurements
TSP Calibration for IGBT to MOSFET



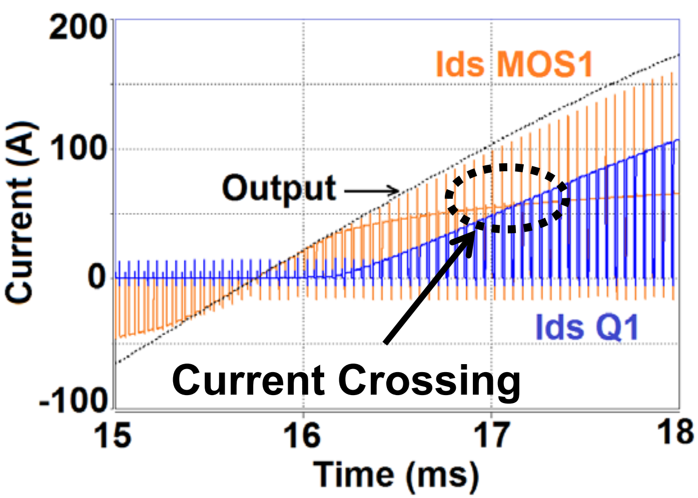
Analysis: Inverter Electro-thermal Simulation - VTech Module Electrical Waveforms

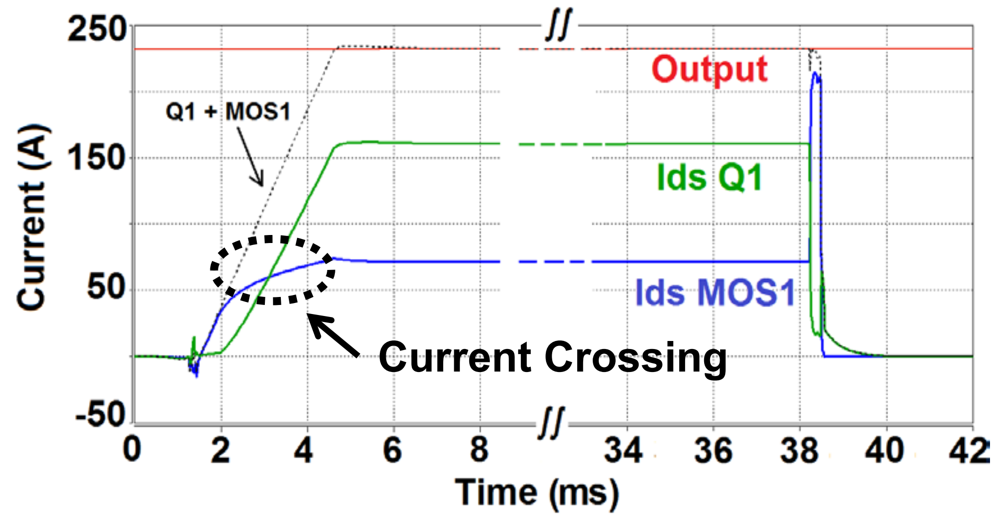


Inverter Output

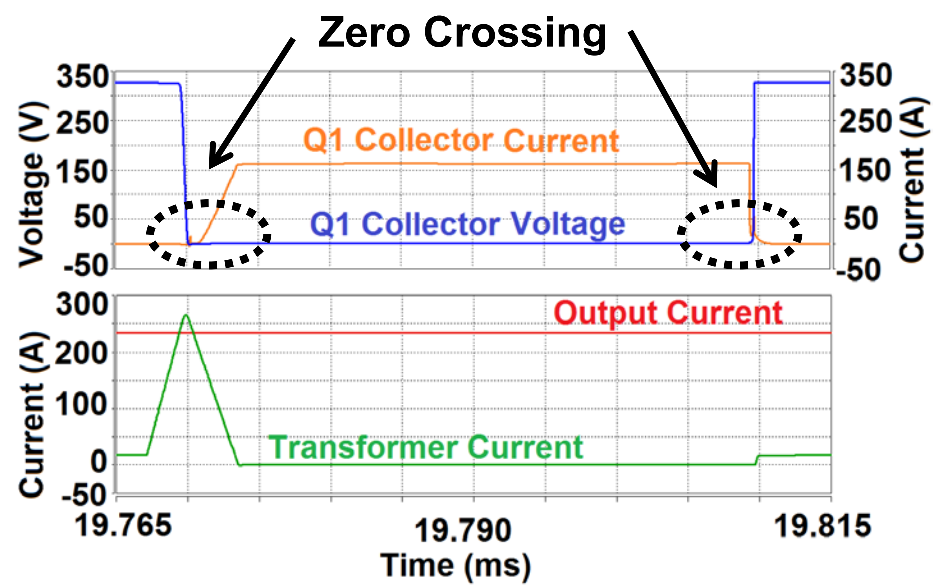
P_{out} : 20 kW
f_{out}: 60 Hz
f_{sw} : 20kHz
I_{out}: 160 A
V_{bus}: 114 V

Analysis: Inverter Electro-thermal Simulation - VTech Module Electrical Waveforms

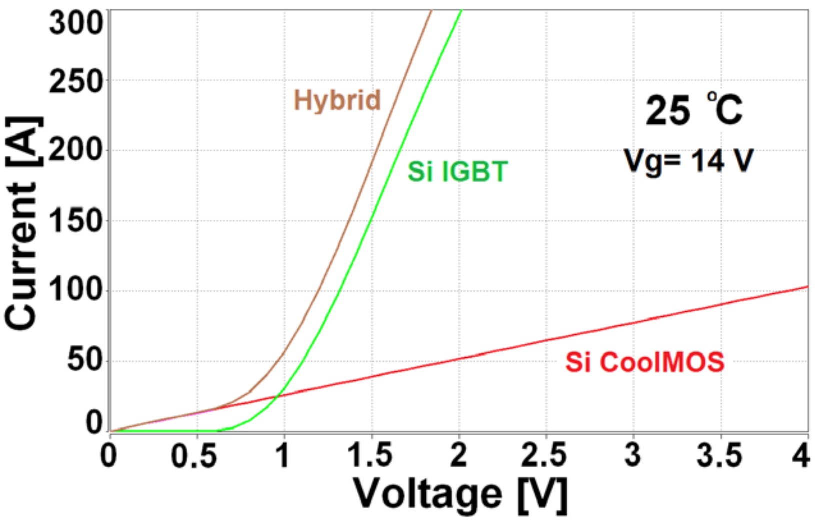


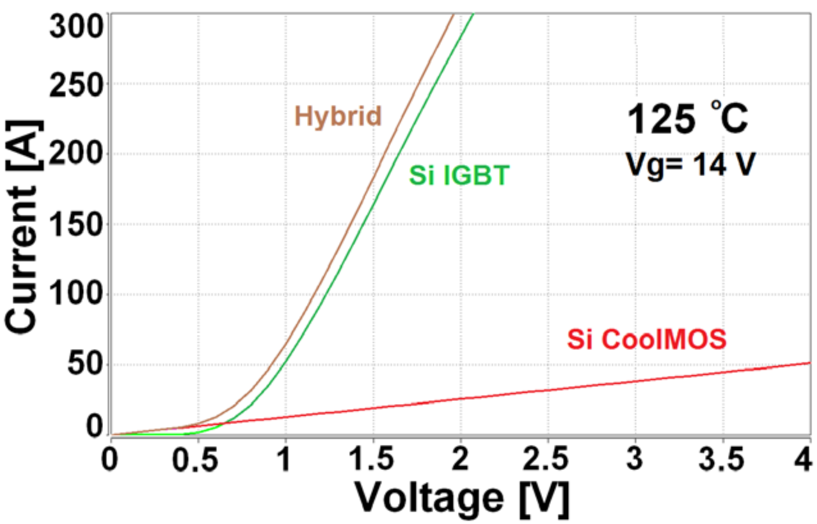


A variable timing scheme that uses a voltage sensing circuit to detect the zero voltage crossing condition is used to determine the main switch turn-on time. The transformer current allows enough energy to discharge the main device (Q1) voltage to zero prior to main device conduction, enabling the zero-voltage switching condition.

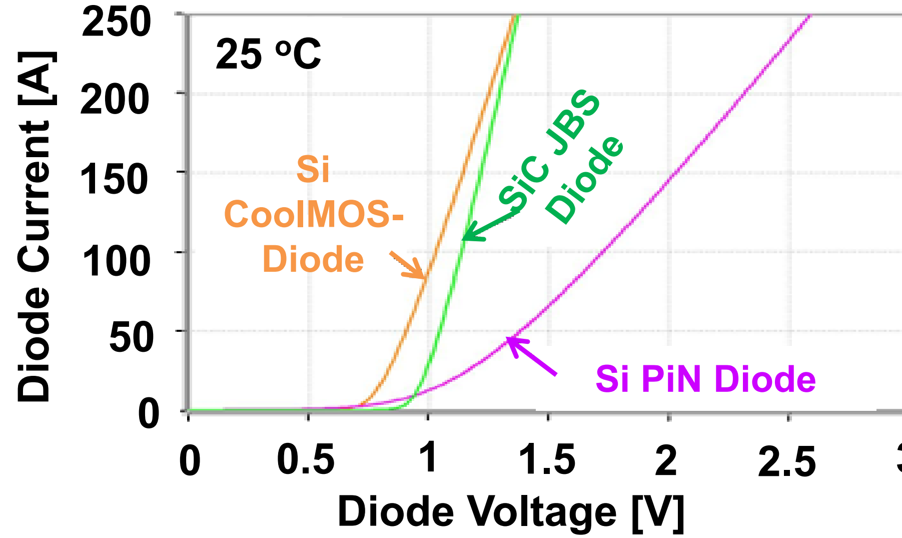


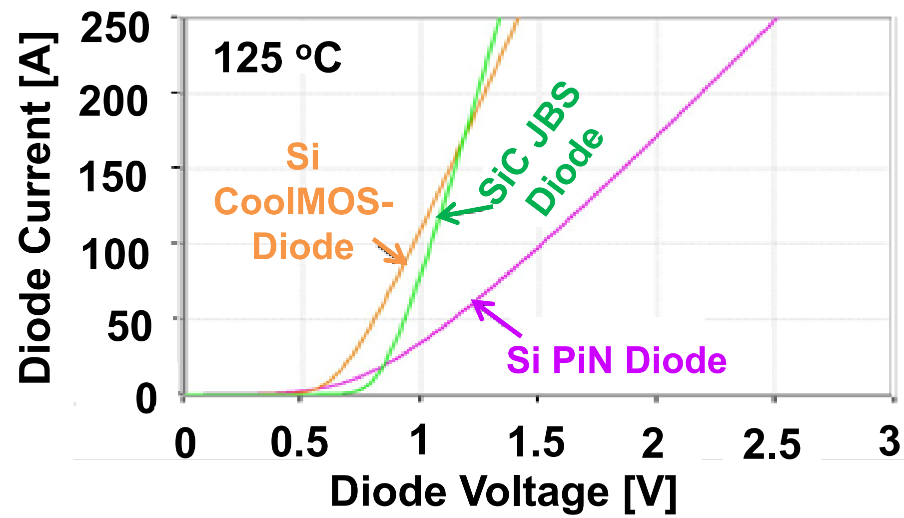
Analysis: Paralleled Si IGBT, CoolMOS, Diodes





Analysis of current sharing of paralleled Switches (Si IGBT and CoolMOS)





Analysis of current sharing of paralleled Diodes (Si PiN, CoolMOS-body Diode, SiC JBS Diode)

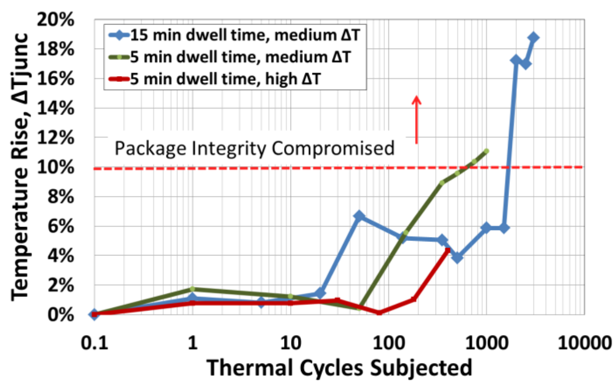
Application: Package Reliability Prediction

Physics-of-Failure Models

- Coffin-Manson
- Norris-Landzberg
- Energy Partitioning
- Strain-Range Partitioning

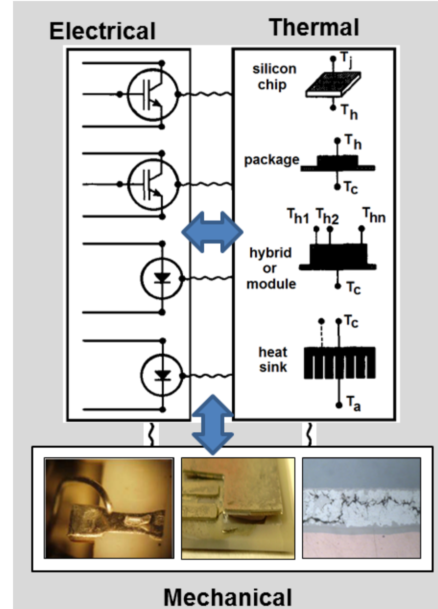
High-speed Transient TSP

Used to detect changes in thermal resistance of buried-interfaces caused by thermal cycling damage.

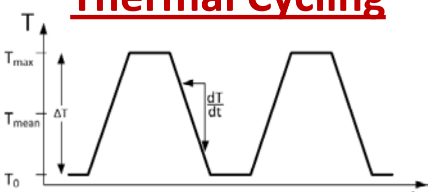


Degradation and Monitoring

Reliability Simulations



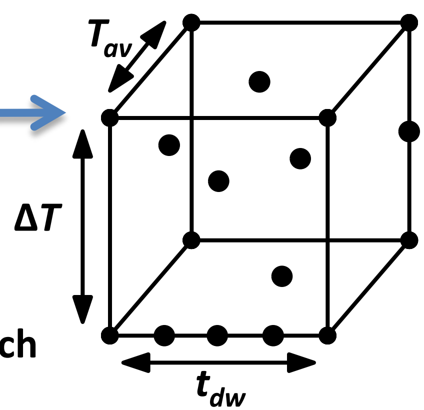
Variable Ramp-Rate Thermal Cycling



Mean Temp.	Temp. Swing	Dwell Time
$T_{av,1}$	ΔT_1	$t_{dw,1}$
$T_{av,2}$	ΔT_2	$t_{dw,2}$
…	…	…
$T_{av,i}$	ΔT_i	$t_{dw,i}$

Multiple cycling parameters for each DBC stack construction.

Design-of-Experiments



$N_f(T_{av}, \Delta T, t_{dw})$

Technology Dependent Reliability Models

Summary

- Validated Delphi Viper simulations for full range of short circuit fault conditions: collector voltages, gate-drive parameters, and initial temperatures.

- Electro-thermal-mechanical simulations used to evaluate thermal stresses in Delphi Viper double-sided cooling power module for nominal and fault operating conditions.

- Performed a range of thermal cycling and thermal shock degradations to characterize mechanical reliability of two DBC stack types.

- Used new enhanced TSP measurement system to validate thermal cross-coupling between die within VA Tech soft switching modules.

- Performed full electro-thermal simulations and validations for VA Tech soft switching module in propulsion inverter operation at P_{out}= 50 kW @ 20 kHz.

Future Work

- Include advanced Wide-Bandgap semiconductor device models in simulations to optimize high current density, low thermal resistance, and soft-switching modules.
- Develop electro-magnetic package/system interconnect models.
- Perform EMI simulations using electro-magnetic package/system interconnect models, electro-thermal semiconductor models and thermal-network-component models.
- Determine grid storage/inverter applications for bi-directional vehicle chargers and develop circuit simulation scripts for chargers operating in these conditions.
- Perform simulations and evaluate impact of advanced technology power semiconductors and module packages in bi-directional vehicle charger storage/inverter applications.